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THE D- AND E- REGIONS

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12 September 1974

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The chemistry of the E-region is fairly well understood and even many of the dynamical complications of this region have been successfully modeled on individual bases. Some of the major remaining problems of this region are discussed, in particular the nitric oxide concentration, a gas affecting the ratio of the two major E-region ions, O_2^+ and NO^+. The D-region is much simpler than the E-region from a dynamical point of view but extremely much more complex from a chemical standpoint. Recent results from a study of the

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D-region under bombardment by solar protons is emphasized. In particular, the positive ion structure of the D-region is well understood under such conditions in comparison to the quiet D-region. The negative ion problem is not well understood because of a lack of observational data below 70 km. It can be shown, nevertheless, that substantial detachment of electrons from negative ions is taking place in the daytime. At night, the problem of the negative ions is virtually irrelevant in regard to the electron concentrations because the electrons appear to be irretrievably lost by attachment to O_2 below about 75 km.

Preface

This paper was presented by the author at the Summer Advanced Study Institute held at the University of Leige (Sart Tilman Campus) during 29 July to 9 August 1974. There were about 30 lectures given in all. All the lectures, including the material here, will be published as chapters in a book entitled, "Atmospheres of Earth and the Planets". The book will probably be published early in the Spring of 1975. The Institute was sponsored by the Advanced Research Projects Agency (ARPA), the Defense Nuclear Agency (DNA), the Lockheed Palo Alto Research Laboratory, the Office of Naval Research (ONR), and the U.S. Army Research Office.

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Illustrations

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The D- and E-Regions

1. INTRODUCTION

The peaks of the daytime E- and D-regions are considered to obey a simple $q = \alpha_{eff}[e]^2$ law, where q is the ionization production rate, α_{eff} is the effective electron loss coefficient, and [e] is the electron concentration. Beyond this, the similarity of these adjacent ionospheric regions is inconsequential.

E-region chemistry is fairly simple, the region being dominated by the presence of O_2^+ and NO^+ ions. The conversion of major precursor ions like N_2^+ and O^+ into NO^+ and O_2^+ ions is rapid enough at these altitudes (about 90-150 km) to prevent these ions from becoming prominant species. However, meteor ions can occasionally be very important, especially when dynamical processes are active. Transport effects and the presence of meteor ions can complicate determinations of α_{eff}.

(Received for publication 12 September 1974)

The chemistry of the D-region is far more complex than any other portion of the ionosphere because it is the only ionospheric section where three-body processes are important. The formation of negative ions in the ionosphere originates with the processes $e + O_2 + O_2(N_2) \rightarrow O_2^- + O_2(N_2)$ and only at D-region altitudes are neutral concentrations large enough to provide for significant O_2^- formation. Radiative processes like $e + O_2 \rightarrow O_2^- + h\nu$ are too slow.

D-region dynamical processes on the other hand are generally unimportant in regards to the movement of charged particles. However, the transport of minor neutral species, especially NO, is important to both this region and the E-region.

2. E-REGION

The E-region has been more or less successfully modelled by Keneshea et al.[1] Their work has been extended into the F1 region by Torr et al.[2] Swider[3] has provided considerable discussion concerning many of the details required for accurate modelling of the E-region. A historical account of the development of E-region research has recently been given by Bates.[4]

2.1 E-Region Recombination Coefficient

The electron recombination coefficient of the E-region may be written as[3]

$$\alpha_{MR} = \frac{\alpha(NO^+)[NO^+] + \alpha(O_2^+)[O_2^+] + \alpha(M^+)[M^+]}{[NO^+] + [O_2^+] + [M^+]}$$

in order to accommodate the sometimes presence of atomic metallic ion concentrations, $[M^+]$. These ions are normally absent, resulting in

$$\alpha_{MR} = \alpha_M = \frac{\alpha(NO^+)[NO^+] + \alpha(O_2^+)[O_2^+]}{[NO^+] + [O_2^+]}$$

1. Keneshea, T.J., Narcisi, R.S., and Swider, W. (1970) Diurnal model of the E-region, J. Geophys. Res. 75:845-854.
2. Torr, D.G., Torr, M.R., and Laurie, D.P. (1972) Diurnal and seasonal model of the F_1 layer at medium to high latitudes, J. Geophys. Res. 77:203-211.
3. Swider, W. (1972) E-region model parameters, J. Atmos. Terr. Phys. 34:1615-1626.
4. Bates, D.R. (1973) The normal E- and F-layers, J. Atmos. Terr. Phys. 35:1935-1952.

which, since[5] $\alpha(NO^+) \approx 2\alpha(O_2^+) \approx 4 \times 10^{-7}$ (300/T) $cm^3\ sec^{-1}$, results in a mean recombination coefficient of about 3×10^{-7} (300/T) $cm^3\ sec^{-1}$ for the mid-day E-region where $[NO^+] \approx [O_2^+]$.

The metallic ions deposited by the continual ablation of meteors are most likely to be significant at night when only scattered HL$y\alpha$ and HL$y\beta$ are present to weakly form the nighttime E-region.[6,7,1,8] A meteor ion layer can lead[9] to misleading estimates of the nighttime ionization source[3], as shown in Figure 1.

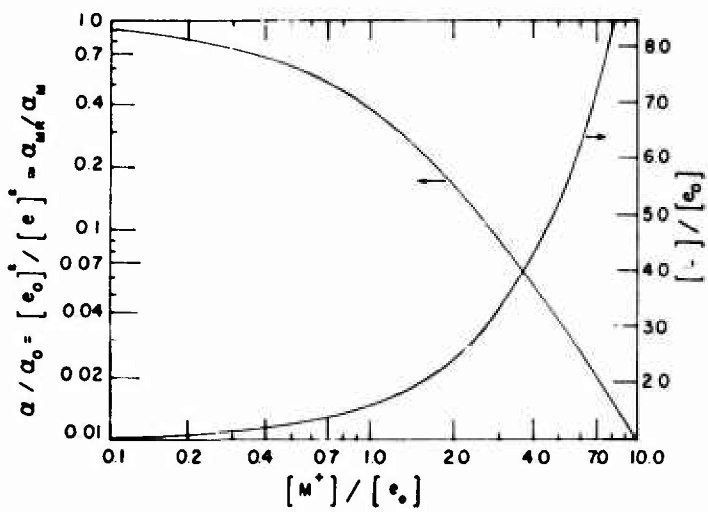

Figure 1. Relative Electron Concentrations and Recombination Coefficients as a Function of the Ratio of Metallic Ions $[M^+]$ to the Original Electron Concentration $[e_0]$ in the Absence of These Ions. The mathematical development is given by Swider[9]. The ionization production rate is constant. If the recombination rate is assumed constant then the increasing (apparent) production rate, q, is given by $q = q_0[e^2]/[e_0^2]$

5. Biondi, M.A. (1969) Electron recombination and ion recombination, Canad. J. Chem. 47:1711-1719.

6. Swider, W. (1965) A study of the nighttime ionosphere and its reaction rates, J. Geophys. Res. 70:4859-4873.

7. Ogawa, T., and Tohmatsu, T. (1966) Photoelectronic processes in the upper atmosphere, 2, the hydrogen and helium ultraviolet glow as an origin of the nighttime ionosphere, Rep. Ionosphere Space Res (Japan) 20:395-417.

8. Tohmatsu, T., and Wakai, N. (1970) An investigation of nighttime ionizing sources in low- and mid-latitudes, Ann. Geophys. 26:209-211.

9. Swider, W. (1969) Processes for meteoric elements in the E-region, J. Atmos. Terr. Phys. 17:1233-1246.

Electron precipitation may occasionally be important at mid-latitudes.[10] However, such events may be of more significance to the D-region in regards to explaining[11] the "winter anomaly". The E-region model of Keneshea et al[1] suffices even for high latitudes[12] under quiet conditions (Figure 2).

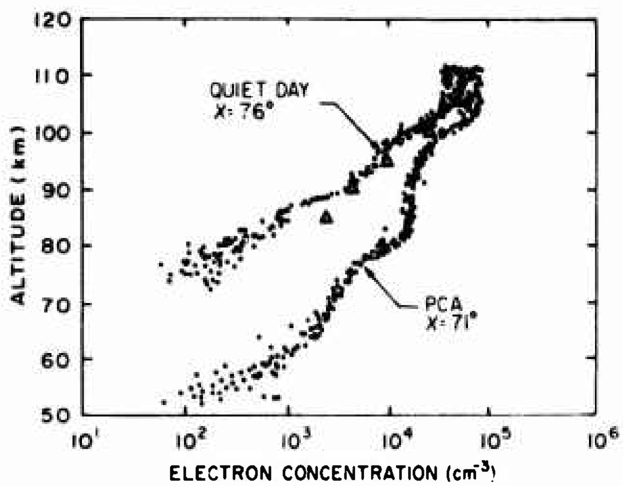

Figure 2. The Quiet Day Electron Concentration of Grieder and Burt[12] at Thule, Greenland for 22 March 1971 as Compared to the E-region Model (Δ) of Keneshea et al[1] for the Same Solar Zenith Angle, 76°. Data[12] obtained during a PCA event on 6 April 1971 is also shown

Attempts to determine α_{eff} from bulk analysis of the E-region and relate it to α_M have failed for a variety of reasons in addition to the sometimes strong layering of meteor ions. E-region eclipse studies in the earlier days invariably led[13] to α_{eff} values of $0.5 - 2.0 \times 10^{-8}$ $cm^3\ sec^{-1}$, the importance of X-rays at totallity being recognized[14] in the mid-fifties and implying that α_{eff} could be[15] as great as 10^{-7} $cm^3\ sec^{-1}$. Eclipse studies have proved to be a difficult way of determining α_{eff}.

10. Nicolet, M., and Swider, W. (1963) Ionospheric conditions, Planet. Space Sci. 11:1459-1482.
11. Manson, A.H., and Merry, M.W.J. (1970) Particle influx and the 'winter anomaly' in the mid-latitude (L=2.5 – 3.5) lower ionosphere, J. Atmos. Terr. Phys. 32:1169-1181.
12. Grieder, W.F., and Burt, D.A. (1973) Rocket measurements of production and ionization at Thule, Greenland during a PCA event, Space Res., 13:575-580.
13. Ratcliffe, J.A. (1956) A survey of solar eclipses and the ionosphere, Spec. Suppl. J. Atmos. Terr. Phys. 6:1-13.
14. Hunaerts, J., and Nicolet, M. (1955) Interpretation of ionospheric results during eclipses, J. Geophys. Res. 60:537-538.
15. Ratcliffe, J.A. (1956) Summary, Spec. Suppl. J. Atmos. Terr. Phys. 6:306-307.

Measurements of the relaxation time of the ionosphere, Δt, also failed[3] since the negative values sometimes attained could hardly be correlated with $\alpha_{eff} = 1/(2\Delta t[e])$ since α_{eff} must be a positive number if it represents α_M. Palluconi[16] and other workers he cites have attempted to clarify the problem by use of a modified form of the E-region electron continuity equation. However, inclusion of a simple divergence term has not led to physically meaningful results even if there is a consistent pattern which suggests effects linked to the Sq current system or some other sort of transport effect.[3,17]

2.2 E-Region Ion Transport

Mid-latitude sporadic-E is generally believed to result from the buildup of ions by the action of winds and wind shears in conjunction with the presence of the earth's magnetic field. These sporadic-E layers apparently are quite common at night and sunset and at Arecibo are most pronounced during winter months.[18] Keneshea and MacLeod[19] have successfully modelled a sporadic E-region experimental profile using the specific wind profiles measured at the same time as the ion composition data of Narcisi et al (cited by Keneshea et al).[1] Similar studies have been undertaken by Chen and Harris.[20] The sporadic-E layers are often but not always composed of meteor ions. Meteor showers have been observed to strongly perturb the nighttime E-region,[21] (see also Swider[6] for older references).

2.3 Nitric Oxide

The minor neutral gas NO is important in E-region chemistry. It is a major factor in the existence of NO^+ ions because the process $O_2^+ + NO \rightarrow NO^+ + O_2$ is generally competitive with electrons as an O_2^+ loss mechanism. In fact, at night

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16. Palluconi, F. D. (1963) The determination of the world-wide effective recombination coefficient of the E-region, Ionosph. Res. Lab. Sci. Rep. 198, PA. State Univ.
17. Butcher, E.C. (1974) The effect of the Sq current on the determination of the effective recombination coefficient of the E-region, J. Atmos. Terr. Phys. **36**:177-181.
18. Rowe, J.F. (1974) Downward transport of nighttime E_s layers into the lower E-region at Arecibo, J. Atmos. Terr. Phys. **36**:225-234
19. Keneshea, T.J., and MacLeod, M.A. (1970) Wind-induced modification of E-region ionization profiles, J. Atmos. Terr. Phys. **27**:981-984.
20. Chen, W.M., and Harris, R.D. (1971) An Ionospheric E-region nighttime model, J. Atmos. Terr. Phys. **33**:1193-1207.
21. Rowe, J.F. (1973) A statistical summary of Arecibo nighttime E-region observations, J. Geophys. Res. **78**:6811-6817.

although the prime source of ionization is the ionization of O_2 by scattered HL $y\beta$ radiation,[6,7,1] the dominant ion is NO^+ since the electron concentration is low. Ionization of nitric oxide by the direct HL $y\alpha$ flux is a major twilight ion source[6,22] and ionization of NO by scattered HL $y\alpha$ is important to the lower E-region at night.

The distribution of nitric oxide is not yet well understood. Typical profiles are shown in Figure 3. The profile adopted by Keneshea et al[1] essentially followed Barth's[23] results except at 85 km where a lower value was needed. Meira's[24] data are higher than Barth's[23] but may reflect different atmospheric conditions at mid-latitudes. Tisone's[25] results are for 20°N latitude. The Swider and Narcisi[26,27] results were inferred from auroral ion composition data and suggest (also Barth and Rusch)[28] that NO is enhanced at auroral latitudes.

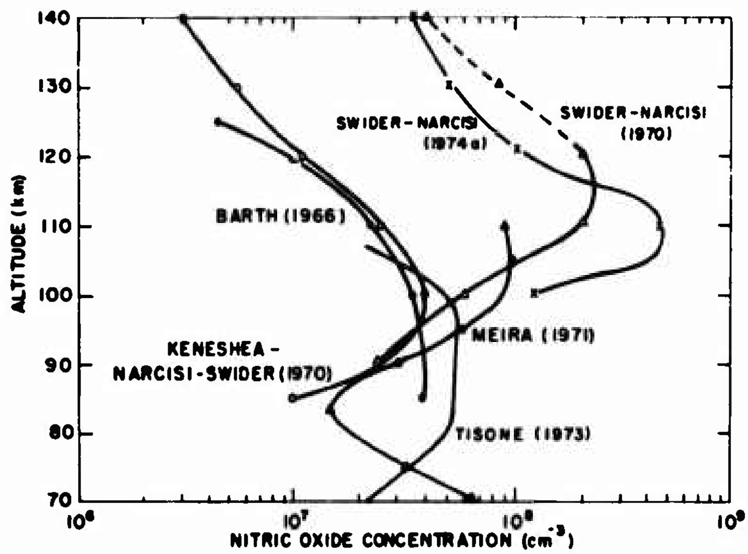

Figure 3. E-Region Nitric Oxide Profiles (See Text)

22. Swider, W., and Keneshea, T.J. (1968) The role of nitric oxide in the sunrise E-region, Space Res. 8:370-376.

23. Barth, C.A. (1966) Nitric oxide in the upper atmosphere, Ann. Geophys. 22:198-207.

24. Meira, L.G., Jr. (1971) Rocket measurements of upper atmospheric nitric oxide and their consequence to the lower ionosphere, J. Geophys. Res. 76:202-212.

25. Tisone, G.C. (1973) Measurements of NO densities during sunrise at Kauai, J. Geophys. Res. 78:746-750.

26. Swider, W., and Narcisi, R.S. (1970) On the ionic constitution of Class I auroras, Planet. Space Sci. 18:379-385.

27. Swider, W., and Narcisi, R.S. (1974) Ion composition in an IBC Class II aurora, J. Geophys. Res. 79:2849-2852.

28. Barth, C.A., and Rusch, D.W. (1971) Satellite measurements of the nitric oxide airglow, I.U.G.G., Moscow.

3. D-REGION

The daytime quiet D-region has not been successfully modelled to date. On the other hand, recent studies of D-region observations during the 2-5 November 1969, PCA event have yielded fairly straightforward interpretations of the positive ion chemistry. The negative ion chemistry is somewhat uncertain but appears to be inconsequential at night for the majority of the D-region because electrons are irretricvably lost below about 75 km by the action of three-body processes producing O_2^- ions.[29] See Mitra,[30] Sechrist[31] and Thomas[32,33] for major D-region reviews.

3.1 The Quiet D-Region

At present there is no understanding of how the initially formed ions in the daytime D-region, presumably NO^+ ions, become converted into oxonium ions, $H_3O^+ \cdot (H_2O)_n$. Figure 4, from the paper of Swider,[34] illustrates that Meira's[24] nitric

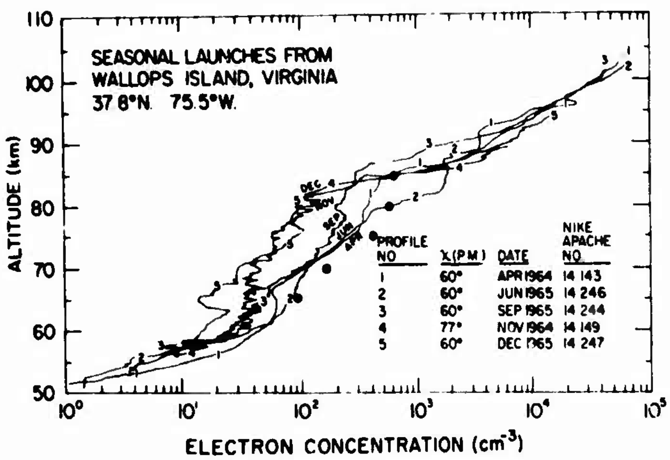

Figure 4. The Observational Data of Mechtly and Smith[35] is Compared to Equilibrium Calculations by Swider[34] With [NO] = 10^{-8} [O_2]. Dissociative recombination rates of 6×10^{-7} cm^3 sec^{-1} for 85 km and 4×10^{-6} cm^3 sec^{-1} for the other altitudes were adopted since NO^+ is the dominant ion at 85 km and oxonium ions dominate at the other altitudes[36]

29. Swider, W., Narcisi, R.S., Keneshea, T.J., and Ulwick, J.C. (1971) Electron loss during a nighttime PCA event, J. Geophys. Res. 76:4691-4694.

30. Mitra, A.P. (1968) A review of D-region processes in non-polar latitudes, J. Atmos. Terr. Phys. 30:1065-1114.

31. Sechrist, C.F., Jr. (1972) Theoretical models of the D-region, J. Atmos. Terr. Phys. 34:1565-1589.

32. Thomas, L. (1971) The lower ionosphere, J. Atmos. Terr. Phys. 33:157-195.

33. Thomas, L. (1974) Recent developments and outstanding problems in the theory of the D-region, Radio Sci. 9:121-136.

34. Swider, W. (1972) Reply, J. Geophys. Res. 77:2000-2003.

35. Mechtly, E.A., and Smith, L.G. (1968) Seasonal variations of the lower ionosphere at Wallops Island during the IQSY, J. Atmos. Terr. Phys. 30:1555-1561.

36. Narcisi, R.S., and Roth, W. (1970) The formation of cluster ions in laboratory sources and in the ionosphere, Advan. Electron. & Electr. Phys. 29:79-113.

oxide profile must be reduced by at least a factor of five if the ionization of nitric oxide is the initial quiet D-region process. In fact, a factor of ten decrease in Meira's[24] mixing ratio of 5×10^{-8} would appear to be appropriate (see also Stobel[37]).

3.2 The Disturbed D-Region

Although the chemistry of the D-region is extremely complex, studies of PCA events or SPE's can be especially worthwhile because the ionization level is much higher than that for normal conditions and varies only very slowly with time. Swider and Narcisi[38] have shown that the modelling of the nighttime D-region during a PCA event is quite feasible. Figure 5 represents the ion composition at night

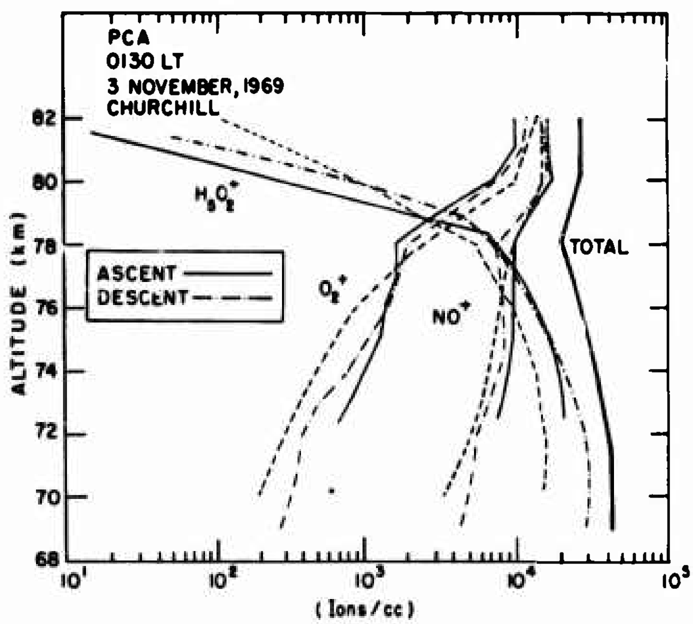

Figure 5. Nighttime Major Positive Ions in a PCA Event[39] as Compared to Model Calculations by Swider and Narcisi[38]

37. Strobel, D.F. (1972) Nitric oxide in the D-region, J. Geophys. Res. 77:1337-1339.

38. Swider, W., and Narcisi, R.S. (1974) A study of the nighttime D-region during a PCA event, J. Geophys. Res., to be published.

39. Narcisi, R.S., Philbrick, C.R., Thomas, D.M., Bailey, A.D., Wlodyka, L.E., Baker, D., Federico, G., Wlodyka, R., and Gardner, M.E. (1972) Positive ion composition of the D- and E-regions during a PCA, pp 421-431 in J.C. Ulwick (ed.) Proc. COSPAR Symp. Solar Particle Event of November 1969, AFCRL-72-0474.

for an ionization level of about 300 ion-pairs cm^{-3} sec^{-1} for all altitudes shown. The results are compatible[38] with the observational data in regards to the major ions O_2^+, NO^+ and $H_5O_2^+$. However, the chemistry of certain of the minor ions is doubtful since some of the rate coefficients must be estimated. A single rate coefficient was adopted for all ion-ion recombinations. This appeared to be permissible because ion-ion recombination is a minor loss process for positive ions over this altitude region; oxonium ions recombining with electrons at a rate at least ten times faster than as with negative ions.

Analysis of a previous PCA event[29] yielded an approximate formula for the electron concentration at night

$$[e] = \left\{ (L(A)^2 + 4\alpha_D q)^{1/2} - L(A) \right\} / 2\alpha_D$$

where $L(A) = k_1 [O_2]^2 + k_2 [O_2][N_2]$, is the electron loss rate and O_2^- formation rate (sec^{-1}) and $\alpha_D \sim 4 \times 10^{-7}$ cm^3 sec^{-1}, with q the ionization production rate. This equation, uncertain by a factor of two near 80 km, attains greater accuracy with decreasing altitude as it collapses to the simpler form,

$$[e] \simeq q/L(A).$$

The effective recombination coefficient thus becomes

$$\alpha_{eff} \equiv q/[e]^2 = L(A)^2/q$$

being directly proportional to the FOURTH POWER of the total neutral concentration and inversely proportional to the ionization rate.

The ratio of the total negative ion population to that of the electrons is now given[29] by

$$\lambda = \frac{\sum_i [n_i^-]}{[e]} \simeq \frac{\sum_i [n_i^-]}{q/L(A)} \approx \frac{(q/\alpha_i)^{1/2}}{q/L(A)} = \frac{L(A)}{(q\alpha_i)^{1/2}}$$

with α_i representing the mean ion-ion recombination coefficient which appears to be about 1×10^{-7} cm^3 sec^{-1} within a factor of two.

Electron precipitation other than in auroras may influence the D-region also, in a less dramatic way than in a PCA event. Earlier in the text we suggested it was generally not important at mid-latitudes. There is a zone just equatorward of the auroral zone where D-region electron precipitation is most common.[40] Weak electron precipitation events are most significant at night since solar ionization effects are absent except for scattered HL $y\alpha$ radiation. Gough and Collin[41] report that at South Uist (L = 3.5) precipitating electrons are the dominant nighttime D-region ionization source 15 ± 11 percent of the time during solar minimum and about 35 ± 20 percent during solar maximum.

Besides electron precipitation and sporadic meteor effects, cosmic X-rays may also contribute to D-region ionization, particularly at night. Svennesson et al[42] have studied VLF signal phases along several paths and found effects related to the stellar X-ray sources Sco XR-1, Cen XR-2, Cen XR-4 and possibly Tau XR-1. Baird and Francey[43] have argued that restriction of electron precipitation effects to $L \gtrsim 2$ would explain many of the conflicts in VLF data, noting, as compatible, the fact that the X-ray effects discussed by Svennesson et al[42] all concern VLF paths with midpoints at $L < 1.7$. A rough picture thus emerges in which for the nighttime D-region cosmic X-ray sources can be important over the region $0 \leq L \lesssim 2$, with electron precipitation effects becoming more pronounced with increasing geomagnetic latitude, peaking near 70°. Meteor ion effects, coupled to the meteor influx and transport effects, compound the problem.

3.3 Daytime Negative Ion Population

The negative ion chemistry of the daytime D-region must be understood in detail because electrons may be detached from negative ions through solar processes. The most direct way is photo-detachment. In this case the photo-detachment cross section of the negative ion must be reasonably well known as a function of wavelength. Except for a few ions, even the threshold for such processes are unknown.

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40. Whalen, J.A., Buchau, J., and Wagner, R.A. (1971) Airborne ionospheric and optical measurements of noontime aurora, J. Atmos. Terr. Phys. 33:661-678.

41. Gough, M.P., and Collin, H.L. (1973) Energetic electron precipitation as a source of ionization in the nighttime D-region over the mid-latitude rocket range, South Uist, J. Atmos. Terr. Phys. 35:835-850.

42. Svennesson, J., Reder, F., and Crouchley, J. (1972) Effexts of X-ray stars on VLF signal phase, J. Atmos. Terr. Phys 34:49-72.

43. Baird, G.A., and Francey, R.J. (1972) Comments on the ionospheric detection of cosmic X-ray phenomena, J. Geophys. Res. 77:1966-1970.

A less direct process is associative detachment in the sense that primary agents like atomic oxygen and $O_2(^1\Delta)$ are generated in conjunction with the daytime ozone chemistry. These species react with O_2^- to free the electron. They also react more indirectly by reducing complex negative ions to simpler ions more susceptible to photo- or associative detachment processes.

The role of photo-detachment and atomic oxygen is illustrated in Figure 6. The sudden jump in the electron concentration near $\chi = 98°$ is a detachment effect primarily as a result of the reaction $O_2^- + h\nu \rightarrow O_2 + e$. Detailed computations show that at $\chi = 97.45°$, the rate at which electrons are being produced by this process is 2.39×10^2 cm^{-3} sec^{-1} with $O_2^- + O \rightarrow O_3 + e$, yielding 1.26×10^1 electrons cm^{-3} sec^{-1} as the second most productive electron source, not including the ionization production rate, 1.56×10^3 cm^3 sec^{-1}. At $\chi = 89.78°$, the yields of these processes are about equal, 8.47×10^2 cm^{-3} sec^{-1} and 8.72×10^2 cm^{-3} sec^{-1}, respectively. According to the rate coefficients used, (see Swider and Keneshea)[44] the yields of these reactions will be equal when $[O] = 1.1 \times 10^9$ cm^{-3}.

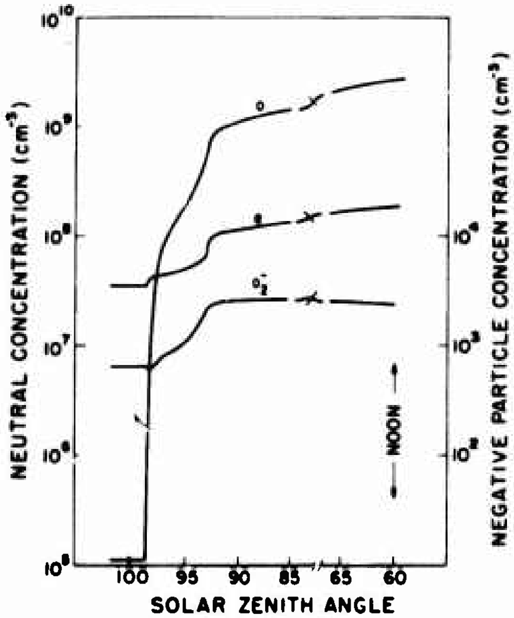

Figure 6. Computed[44] [O], [O_2], and [e] Concentrations at Sunrise (70 km) for a PCA Event

44. Swider, W., and Keneshea, T.J. (1972) Diurnal variations in the D-region during PCA events, pp 589-636, in (J.C. Ulwick, Ed.) Proc. COSPAR Symp. Solar Particle Event of November, 1969, AFCRL-72-0474.

The initial rise in electrons thus appears to be a result of photo-detachment, associative detachment becoming important near about $\chi = 93°$ when sufficient O is present. However, atomic oxygen also acts to reduce the more complicated ions to simpler species, for example, $O + CO_3^- \rightarrow O_2^- + CO_2$, which are more readily subject to detachment processes. The initial rise of atomic oxygen is a result of the photo-dissociation of O_3 by visible light. Photo-dissociation of O_3 in the UV becomes more important for $\chi \leq 94°$. At sunset, the finite lifetime of atomic oxygen, about 20 min at 70 km, will contribute to [e] being somewhat larger, for the same χ, at sunset than at sunrise (see also Adams and Megill),[45] contributing to a sort of hysteresis loop for [e] vs χ.

Minor neutral gases may also exert a profound effect upon the negative ion chemistry. Thus, inclusion of NO_2[44] in daytime PCA D-region calculation results in reduced 30 MHz absorption. This effect is caused by the more rapid formation of negative ions less readily destroyed by detachment processes for the same chemistry considered leading to fewer electrons and hence less absorption at 30 MHz.

4. CONCLUSIONS

It appears that the physics of the mid-latitude E-region is generally well understood. Some details regarding transport processes, particularly in regards to the NO distribution, require further analysis. The positive ion chemistry of the disturbed D-region is reasonably known. More work is required in order to properly interpret the quiet D-region. The negative ion population distributions are unclear for either D-region condition. Laboratory work is needed for further clarification. At night, the negative ion chemistry appears to be irrelevant in regards to the electron chemistry.

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